Astronomy's Conceptual Hierarchy

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I. Introduction

Why are the fundamental concepts of astronomy so difficult for our students? Many teachers of astronomy at pre-college and college levels view students as ill-prepared for their courses. Students do not understand fundamental concepts on which teachers hope to build. Students are not familiar with the motions in the heavens, the moon's phases, the earth's seasons, the nature of light, or the sizes and scale of astronomical systems. The graphical and visual representations that we use throughout our courses (spectra, light curves, H-R diagrams) appear foreign and strange. Equations and simple order-of-magnitude estimations are within the experience of our students, but are rarely useful to them or reproducible by them.

Teachers of astronomy may wonder whether our own teaching and curricula are to blame for our students' difficulties. We change demonstrations, assignments, the order of topics, and textbooks anticipating improvement in student understanding. Others hypothesize that students' prior courses in science are at fault. This frequently takes the form of a cascade of blame from professors to high school teachers to junior high teachers to elementary teachers to parents of pre-schoolers. Three explanations arise repeatedly concerning student preparation, that: students do not have adequate exposure to astronomy prior to our own courses, teachers at lower levels are ineffective because they lack astronomical knowledge, and, even if astronomical topics are taught, fundamentals are never mastered, because the pace of instruction is so rapid. Examining each of these claims individually is an instructive start to understanding the problem.

First of all, astronomy is not a sparsely taught, uncommon subject, but a popular topic throughout the pre-college curriculum. In elementary school, students first are exposed to seasons, moon phases, and the planets. In junior high school, students begin their study of the solar system and stars, usually as a part of their earth science course. Somewhere between 10%-15% of US high schools offer semester or yearlong elective courses in astronomy (Sadler 1992). Introductory college courses in astronomy are popular and often convenient ways to fulfill science requirements. Enrollments in introductory science courses in which astronomy has a major role are estimated (Figure 1) drawing upon the results of several surveys (Hoff 1982, Weiss 1987, Welch 1985). The majority of our high school and college students in astronomy have had substantial exposure to astronomy in grades 7-9. This early instruction in junior high general science and earth science courses dwarfs later enrollment in introductory astronomy courses.

Second, a belief held by many science teachers is that student learning is highly dependent upon the subject matter knowledge of their teachers. In most states, changed certification requirements, requiring a major in a subject matter field and disallowing education degrees, seem to reflect that belief. Research does not support the conclusion that such conditions make a difference. Teachers with heavy coursework and higher degrees do not either appear to have students that score higher on standardized tests or are held out as exemplars by their supervisors (Yager 1988). Nor are the difficulties
that students have in astronomy the result of being taught by teachers without adequate subject matter knowledge. Recent advances in cognitive psychology show that learning is a process of constructing knowledge, not simply of transmission of knowledge from expert to novice. Although it can be of benefit for teachers to know the subject that they are teaching, advanced coursework does not guarantee more effective teaching. Nevertheless, while many elementary school teachers may lack courses in the physical and earth sciences, at the junior high school and high school level teachers have much more substantial backgrounds. Among teachers who teach a separate astronomy course at the high school level (roughly 15% of schools), many own telescopes and most subscribe to magazines such as Sky & Telescope or Astronomy. An amazingly high 77% consider themselves amateur astronomers (Sadler and Luzader 1988).

![Diagram](image)

**Figure 1.** Enrollment in Courses Teaching Astronomy at the Introductory Level.

Thirdly, what then is the content in pre-college astronomy courses? Don't introductory courses cover the fundamentals? The answer is that the key concepts are rarely covered to the extent that promotes mastery. Students tested at the start and end of introductory astronomy courses have the same mistaken ideas about how the natural world behaves. For example, many do not believe that light propagates as particles with differing energies, that gravity is not a result of air pressure, or that the Sun is the only star in our solar system (Lightman and Sadler 1992). Astronomy is no different from other sciences in this regard. This circumvention of fundamental concepts is exacerbated in high school astronomy, where most teachers use popular college level textbooks, crammed with information from archeoastronomy to cosmology. Junior high earth science texts cover fewer of the same difficult concepts, but emphasize the field's specialized vocabulary. Elementary curricula are more selective, but often present concepts that are beyond the developmental level of most students. Rare is the fifth grader who can take the "God’s-eye" view of our solar system, while living in a geocentric world. For these students, explaining seasons as resulting from "the tilt of the earth's axis" rather than the apparent position of the sun in our sky, is profoundly unproductive, since most of them do not view two-dimensional drawing as representing a three-dimensional model. Many explain artists' renditions of orbits as evidence for pictures taken from space by astronauts (Touger 1985).

Courses at every level appear to be collections of interesting topics with associated vocabulary. There is precious little thought put into how students structure what they learn. Historical (from Hipparcus to modern astronomy) or structural perspectives (progressing from the earth outward) appear logical and helpful to us, as astronomical cognoscenti. There is little evidence that students find these ways of organizing knowledge beneficial. A case in point is the unpopularity of the "new math"
in the 1960's. Although the set-theoretic foundations of mathematics are useful to professional mathematicians, they appear to be a disastrous way of organizing mathematics for youngsters. What, then, is a productive way to structure an introductory astronomy course to optimize student learning? Which topics are prerequisites for others or can they all be taught without regard to order? Is there a natural progression in which most students come to understand astronomy or is it haphazard, idiosyncratic, and unpredictable? These are the questions which I and many of my colleagues have set for ourselves and which are discussed in this paper.

II. Studies of children's ideas

The educational psychologist, David Ausubel, was first to recognize the importance of students' prior knowledge. He posited "the unlearning of preconceptions might very well prove to be the most determinative single factor in the acquisition and retention of subject-matter knowledge (Ausubel 1978)." Ausubel makes a clear distinction between "meaningful" and "rote" learning. Meaningful learning denotes the incorporation of new concepts and facts into a student's scheme of the world that results in the restructuring of the student's knowledge, while rote learning is a process in which a student's existing scheme is unaffected. New information is never fully processed and connected to prior knowledge, but stored in isolation (and promptly forgotten when the semester is over).

Ausubel's ideas are at the root of much of the research on children's understanding of science. Probes of children's ideas have taken the form both of student interviews and written instruments. Each has been fruitful. Open ended interviews have served to expose domains that are fertile for more extensive investigation and have revealed the presence, but not the relative popularity, of a multitude of student ideas. These ideas are often quite fantastic and often seen as humorous by adults. As an example, I recently overheard a wonderful question directed by a six year old to a seven year old after noticing the moon in the daytime sky, "Is the sun ever out at night?" A lively discussion ensued. It was clear that this youngster had an alternative view of the reason for day and night which did not involve the sun.

Written instruments have aided in examining the beliefs of larger populations and have helped to establish which ideas appear to be shared by many students and those that are more idiosyncratic. Often these individual ideas are part of a much larger and structured "alternative framework (Driver and Easley 1978)." A good example is the Aristotelian framework, refuted by Newton, in which objects come to rest unless a constant force is applied (Caramaza, McCloskey and Green 1981, Brown and Clement 1986, Clement 1986). In astronomy, a common alternative framework is one in which the distance between objects is roughly the same as the size of the objects. For these students, lunar eclipses are moon phases, stars are crowded into our solar system and our spaceships can easily visit other galaxies. This view provides no context for the elaborate methods of the astronomer used to establish sizes and distances. Why use spectroscopy to measure composition if we can travel to and sample stars?

Several studies with application to the learning of astronomy have been carried out. They deal with a range of topics. It is not the purpose of this paper to review them, but the reader may wish to consult them for in depth treatments of student difficulties in each of these areas:

- cosmography (the study of the earth in space) (Nussbaum 1979, Sneider and Pulos, Vosniadou and Brewer 1987)
• gravity (Gunstone and White 1981, Ogar 1986)
• the solar system (Klein 1982, Tregust and Smith 1986, Touger 1985)
• Moon phases (Dai 1990, Cohen and Kagan 1979,
• cosmology (Lightman, Miller, and Leadbeater 1987)
• earth science (Schoon 1988)

The author’s own experience interviewing students about their astronomical ideas began as the initial phase in the development of Project STAR, a high school astronomy curriculum funded by the National Science Foundation. Students were found to have very well developed beliefs about the reasons for day and night, the cause of the seasons, and the moon’s phases that were at odds with those of their teachers (Sadler 1987). Student ideas were documented in the award-winning video A Private Universe (Schneps and Sadler 1988 [Available from the ASP]). Later interviews were carried out by the author, the staff of Project STAR, and teachers consulting to Project STAR. I am particularly indebted to Dr. Anne Young of the Rochester Institute of Technology, Dr. Linda Shore, now of the Exploratorium, and the dynamic team of Jenny and Paul Hickman, now of Belmont High School and Boston University Academy, for their work in this area.

Multiple choice tests can be constructed using the results of interviews and open-ended tests. In these instruments, items are constructed which capture the most prevalent ideas of students along with a scientifically correct answer (Freyberg and Osborne 1985). These tests appear quite normal to teachers until they let their students take them. Since popular notions are included, students inevitably find them more attractive than the scientifically correct answers, even after extensive instruction. This has commonly resulted in two disparate interpretations by teachers. Either they begin to question what their students actually understand or they attack the construction of the item. The latter always proves unproductive since interviews of students produce nearly identical results. These multiple-choice tests can then be given to large populations of students and scored by computer. The target population for the study which I will discuss drew students from grades eight through twelve who were in earth science or astronomy courses. The 1,200 subjects were the students of 22 teachers and took the test at both the start and end of their courses. The full description of the generation and validation of the test have been thoroughly examined in an earlier publication (Sadler 1992).

III. Excursion into Psychometrics

Much has been written about the use of tests as a way to measure student knowledge. A construct that is useful for our analysis is that of difficulty. This does not refer to a teacher’s view of how hard or easy a question is, but the assignment of a numeric value to a particular test item. For a multiple choice item, item difficulty is often described as the fraction of students who chose the correct answer for a particular item within the test population. Items can then be compared based on these values. For example, the following two items were constructed from interviews with children. In a population of high school students taking astronomy or earth science, .66 of the students answered Item 1 correctly:
1. What causes night and day?
   A. The Earth spins on its axis.
   B. The Earth moves around the Sun.
   C. Clouds block out the Sun's light.
   D. The Earth moves into and out of the Sun's shadow.
   E. The Sun goes around the Earth.

   Item 34 was included on the same test. Only .28 of the students answered it correctly.

   Figure 2, The Big Dipper Illustration from Item 34

34. The Big Dipper would have a noticeably different shape to the unaided eye:
   A. if viewed from another star.
   B. if viewed from Pluto.
   C. if you looked at it a year from now.
   D. if you viewed it from China.
   E. never, it would always look the same.

   Of course, the difficulty of a particular test item depends on the population taking the test. One would expect all graduate students in astronomy to get Item 1 right (as indeed Harvard students do), while few kindergartners will select the correct answer. Item 34 might prove more difficult for this population.

   How can a test made up of misconception questions be used to help teachers understand how their students come to understand astronomical concepts? The key is to use the variation in a large population of students to discover the different stages of understanding. This requires a way to measure item difficulty that is independent of the level of the test population, so that novices can be compared to experts. Over 40 years ago, Lord (1952) introduced the idea of an item response model as a way to measure characteristics of test items that is independent of the examinee group. In his model, item characteristic curves are generated which illustrate the relationship between an underlying "latent trait" or ability and the probability of correctly answering the item, \( P(\text{ability}) \). By comparing student performance on the test as a whole (using a non-linear transformation of students' total test scores) to student performance on individual items (the fraction of students correctly answering a particular item), one can measure an item's intrinsic difficulty.

   The model can be expressed as the probability of getting an item correct as a function of the ability of the student. Student ability is measured in units of standard deviation from the mean ability in the idealized, normally distributed population. More recently a model was developed that estimates item difficulty for both correct and incorrect answers (Thissen and Steinberg, 1984). This technique is extremely useful
in analyzing misconception-based multiple-choice tests, where the "wrong" answers are of equal interest as those that are scientifically correct. Using such models, same item difficulties are generated from testing quite different populations. Many test populations can also be added to the dataset to seamlessly increase the statistical power of the model. In this way, it is possible to stretch our students out into a spectrum of ability and begin to understand the variation in comprehension of science concepts.

Let us take as an example the relatively easy question above (Item 1) concerning day and night. A graph of the probability of students selecting each answer as a function of their ability is shown below.

![Graph showing probability of correct answers for different ability levels.]

Figure 3, Item 1. What causes night and day?

This plot shows that students of the lowest ability (SD = -22) answer this question correctly about .65 of the time, while students of the highest ability answer the question correctly all of the time. Surprisingly, students of moderate ability (SD = -50) have only a 47% probability of answering this question correctly. Students of low ability (low overall test scores) appear to be at some advantage compared to students of average ability, who are more likely to believe that day and night are caused by the earth’s revolution about the sun. This analysis shows that the "fact" that the earth’s rotation makes day and night is not a fact at all. For many students, the idea is in conflict with the earth’s orbit about the sun. It is the integration of such "facts" with the world that is misunderstood, not the existence of these facts by themselves. When called upon to predict student responses to this question, teachers inevitably choose that many students think that the sun goes around the earth. Although this seems reasonable given the historical development of the field, few students in grades 8-12 believe it, as shown in figure 3.

The problem of integrating specialized scientific information into children’s frameworks is also evidenced in the results of the National Assessment of Educational Progress (figure 4). While students at all ages appear to know everyday science facts (e.g. the earth orbits the sun), their ability to integrate information into their world view
is meager. It is not the learning of scientific facts and principles, per se, that is difficult, but coming to terms with their implications in all their variety. That is the challenge in learning and teaching science.

![Graph showing proficiency in science](image)

Figure 4, Proficiency in Science 1986 National Assessment of Educational Progress.

One can go beyond a straightforward interpretation of the item response graph of Item 1 (figure 3) simply as a static model to a description of how students progress though their learning of this concept. Although these graphs are drawn from large populations, students can be thought of as moving from the left to the right of the ability axis as they come to master the subject. This means that as student knowledge climbs as a result of taking a course in astronomy, their ability to answer a question correctly may fall for a period. Many researchers have found this to be the case at all academic levels. The reason for this surprising phenomenon is that instruction often reinforces and strengthens student misconceptions. In figure 3, a corresponding increase in student belief that it is the earth moving about the sun that is cause of day and night is reflected in a decline in the scientific explanation.

One can compare the relative difficulty of items by finding the student ability that corresponds to a probability of .50 of answering the question correctly. Even though there are two values that meet this criterion for some items, we will choose the one with the positive slope, so $P_{\text{item}1}(.50) = -.30$. Let us take as an example a more difficult question, that of astronomical scale (figure 5). Several items on this test examine student understanding in this area. The most revealing has to do with the shape of a constellation when viewed from another star.

In this case, students of low ability answer the question correctly 25% of the time and the convergence of most of the curves to the left is indicative of student guessing at this level. Students of high ability answer correctly over 90% of the time. However, again students of moderate ability do worse on this problem, with only about 12% answering correctly at the -.5 level. This corresponds to an increase in the belief that the pattern of stars that we see in the sky is invariant and remains the same from any viewpoint. This item has a much higher level of difficulty, $P_{\text{item}4}(.50) = .90$. 
Looking at the test as a whole, one can measure the progress of students in units of standard deviations from the mean. In the test population, the average student had a pretest ability of 0.2 SD and a posttest ability of 0.4 SD in conventional classrooms, for a gain of 0.2 SD. This is in contrast to average teacher predictions of a 1.2 SD increase in performance. In experimental classrooms using Project STAR materials, students started at the same level of ability which increases to 0.8 SD, a gain of 0.6 SD. A future paper will examine this experiment in more detail.

Using this technique of calculating item response curves, one can establish the relative difficulty of many astronomical concepts. The majority of the 47 items in the Project STAR Misconception Instrument show similar profiles to those above. They are characterized by:

- A decrease in performance for moderate level students compared to low level students. Students who are engaged in the process of mastering a concept appear to be at a disadvantage to those who are clueless.

- An increase in belief in misconceptions before their eventual decline. Much teaching appears to reinforce students' prior knowledge even though the teacher's explanation may be correct.

- Many questions have difficulties higher than the average student ability. The concepts that teachers select to teach appear too difficult for many students. Ideas that we think students have mastered prior to entry to our classes may not really be understood to the extent that they can be applied.

- Teachers' overestimation of student gains. Students do not reach the levels of performance that their teachers predict on tests constructed by others. It is only on tests that teachers create for their own students that they appear to perform up to expectation.

- Mastery of basic concepts takes time and effort. It often entails a period of confusion. "Coverage" without an extended opportunity to dispel misconceptions and build true understanding appears to be detrimental to student learning.
IV. Hierarchy of Concepts

With the examination of student misconceptions completed let us turn to the surprisingly low student gains on what we as teachers consider relatively easy questions. Slow student progress argues for a reduced conceptual scope of our courses. An attempt to cover too much content appears to leave many students with reinforced misconceptions and a decreased ability to answer many astronomical questions. If we reduce scope, how do we choose which ideas should be covered? Should we only teach the easiest concepts, "dumbing down" our courses? Should we have high expectations for our students and teach the more difficult concepts, hoping they'll straighten out their misconceptions in the process? There is another approach that should be considered, i.e. choosing concepts on the basis of their structural relationship to learning other concepts. In this way, concepts that are required for understanding more difficult ideas should be taught first. When mastery of these ideas is achieved, one can move to harder topics that depend on these prerequisite ideas.

How then can we identify these prerequisites? Measuring item difficulty is not much of a help. Mastery of some randomly chosen easy concept will probably have no influence on learning a difficult one. Yet, within a population of students it is possible to determine which concepts appear to be prerequisite for others. The tool for establishing these relationships is the contingency table. As an example, let us consider the breakdown of women and men in two hospital wards. There are 100 patients, 60 in Ward A and 40 in Ward B. Seventy are male and 30 are females. Using these numbers alone, without knowing who is in which ward, we can calculate the number of females and males in each ward by assuming gender does not affect the probabilities of being in either ward. This is accomplished by treating the marginal totals as probabilities and simply multiplying them together (and dividing by the total) to fill in the interior cells of the table. These are the *expected values* (in italics within table 1A).

<table>
<thead>
<tr>
<th>Table 1A, Expected Values</th>
<th>Table 1B, Observed Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ward A</td>
<td>Ward B</td>
</tr>
<tr>
<td>Male</td>
<td>12</td>
</tr>
<tr>
<td>Female</td>
<td>28</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
</tr>
</tbody>
</table>

If we later carry out a census of the hospital patients, we can find the gender of patients in our wards. These are the *observed values* (italicized and underlined within table 1B). If the expected and observed values are the same, we can safely assume that the probability of being in a ward is independent of gender (we may wish to use a statistical test to be even more certain). However, if the distribution is quite different from expected, a prerequisite relationship may exist. Consider our hospital census result. There are no men in Ward B. The zero in one cell (Male, B) and nowhere else indicates a probable prerequisite relationship between being female and entering Ward B (for example, if it is a maternity ward). Note that what is outlined is not necessarily a correlation (in which diagonal cells in one direction are small compared to the other diagonal). Statistical measures would allow us to calculate the probability of the actual value being significantly different from the expected value with a chi-square test.
This technique was developed and applied to logical and mathematical knowledge by Airasian and Bart in 1973. In the same fashion, we can compare expected with observed values for the answers to two different test items which examine students' conceptual understanding. A cell with a zero value would indicate that one concept may be a prerequisite for another. Of course, the multiple choice format would change the minimum value of the key cell if the items are not similar in difficulty. Fisher's exact test is useful for calculating the probabilities in this case (Bart and Read 1984). By comparing every question on the test with every other, one can establish which are the statistically significant prerequisite relationships in the population of students. This means that 47x47 contingency tables must be tested and evaluated, a job that is straightforward, although time consuming, on a microcomputer.

An example is given in tables 2A and 2B for the contingency table relating the cause of night and day (Item 1) and the knowledge of how long it takes the earth to turn on its axis (Item 21). One can use these numbers to settle the question which comes first, knowing the reason for day and night, or knowing that the earth spins in 24 hours? There are only 30 students in the population (1%) who know the earth turns in 24 hours who do not know the cause of day and night. There are 406 who know the cause of day and night who do not know that the earth turns in 24 hours. There are many who both know or do not know both. One can argue that knowing the cause of day and night is a prerequisite for knowing that the earth spins in 24 hours.

<table>
<thead>
<tr>
<th>Item 1</th>
<th>Item 21</th>
<th>Incorrect</th>
<th>Correct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incorrect</td>
<td>151</td>
<td>272</td>
<td>423</td>
</tr>
<tr>
<td>Correct</td>
<td>648</td>
<td>1165</td>
<td>1813</td>
</tr>
<tr>
<td>799</td>
<td>1437</td>
<td>2236</td>
<td></td>
</tr>
</tbody>
</table>

Even though all of the concepts covered on the Project STAR test reveal student misconceptions and can be placed on a continuum of difficulty, a smaller set are actually related to each other in a prerequisite fashion. Below is a current analysis of items that pass muster (figure 6). This diagram can be interpreted on the following basis. The difficulty of concepts increases vertically. Items that are pointed to by arrows have prerequisites in that there are very few students who hold this concept who do not already understand the prerequisite concept. Yet, students may have prerequisite knowledge and not have the more difficult concept.

This diagram shows that certain elementary knowledge appears prerequisite for more difficult concepts. The understanding of day and night and the earth's yearly revolution about the sun appears to be key to mastery of the sun's motion in the sky, an understanding of seasons, and many other concepts. More importantly, this chart represents the great difficulty students have mastering advanced concepts without processing the prerequisite knowledge. This type of analysis suggests that understanding of science may be constructed much like astronomy's cosmic distance scale; accurate measures of more and more distant objects are dependent on the ways in which we measure closer objects. It may be impossible for students to acquire powerful scientific ideas without great attention to the basics.
V. Conclusion

Student difficulty in introductory astronomy courses has many causes. The interviews and formal testing carried out by Project STAR has revealed two major difficulties. Students hold preconceptions when they enter their courses and learning many astronomical concepts is dependent on mastery of easier concepts.

Students' ideas are quite different from those of their teachers, in spite of the fact that their teachers had to learn these ideas at one time. Many of these ideas are well-developed misconceptions that have been constructed by students from their own experiences and thoughts. These ideas are very resistant to change, but once changed are almost impossible to remember. Teachers rarely can recall their prior, non-scientific conceptual frameworks and tend to teach without attending to their students' prior knowledge. Several studies have shown that these misconceptions can be changed, but conventional courses do little. In many cases, teaching simply strengthens
student misconceptions. The testing of their own ideas by students appears to be a key step in the changing of misconceptions.

Powerful ideas in science are often hierarchical in nature; they build upon one another. Students who do not have the foundation stones firmly in place will find it very difficult to construct an understanding of astronomy. It is important that teachers realize the difference between exposure to an idea and the mastery of it. While many students know that the earth orbits the sun, fewer know how it relates to cycles here on earth.

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References


Discussion

Bisard.

The progression of a student through a set of frameworks from their "initial" ideas to those accepted as "correct" takes several steps. This might be called "Learning." What do you think of this?
Eckroth.

[after talk by Philip Sadler and several other later speakers – below not delivered orally, but written out later]

There are many, widespread misconceptions that are difficult to eradicate – but not impossible. None of us at this meeting, for example, still believes that the seasons are caused by a changing distance to the sun – though we probably did in the lower grades. How did we come to give up that misconception? In the same way that some students did in A Private Universe – by confronting contradictions. Probably in this example, by hearing that travellers to the southern hemisphere find the seasons are reversed there – a clear conflict with the erroneous "explanation." There are many easy observations that clearly conflict with common misconceptions. We should know of them and use them, and disseminate them to teachers at all levels. [Also, nobody in Albuquerque could ever measure the sun at 90° overhead!]

Fraknoi.

Based on these research findings, if you were not merely dean but czar of a school of education, how would you change the way they train teachers to teach science better?

Sadler.

Your hypothetical is quite a fantasy. No one really has such power at the university. But, what future teachers may need most are courses in which they learn science in the same way that we hope they will teach our children. After all, we naturally all teach in the way we've been taught. Lecture/recitation courses at the college level tend to beget themselves at the pre-college level. So, teaching without lecturing, with lots of activities and observations, and with attention to students' prior conceptions would be of great benefit to future teachers.

Pasachoff.

Some of the computer simulations – diskette or CD-ROM – can give students views of solar-system objects from a variety of different aspects, which could help students visualize the reasons for day/night, phases, seasons, and other positional and projective ideas. For example, a student using the Red Shift CD-ROM could look at the Earth from above the pole, from Mars, from the Sun, or from elsewhere and make the Earth (with continents visible) rotate to display the day/night cycle. This individual empowerment has the potential, if properly used, to change day/night, phases, and seasons from their unexpectedly abstract nature to concrete objects in their virtual but apparently actual positions and thus break the logjam in student understanding of these topics.

I have long been struck by your wonderful work on the difficulty that students have with phases and seasons, and have shown A Private Universe to college classes and remediated their deficiencies. Jeanne Bishop is also talking (this meeting) about difficulties students have with "projective" concepts.

Let me ask why it is that we must teach phases and seasons in the K-12 years. Sure, it is common if not universal to do so. But is it just habit? Why is it important that students of any age understand the causes of phases and seasons? At the youngest ages, it may simply be too early in their intellectual development to hope for widespread understanding. Maybe we should be teaching fundamental ideas about modern science – such as the idea that telescopes help us see more clearly, and that telescopes in space can help us still further; or the idea that stars are born, live an ordinary life for a long time, and then die and become one of several end-products – in the early grades instead of phases and seasons. We can get to phases or seasons later, or not at all.
I know that the usual argument for teaching phases and seasons is that these are everyday phenomena. But divers don't have to know about angular momentum to dive into swimming pools, and cats don't have to know these laws of physics to land on their feet when jumping from great heights. We can deal with and appreciate the phases of the moon and the seasons without necessarily understanding the details. And if we are dealing with the moon, I would much rather have students comprehend, as they can at any age, that there are many moons of planets in the solar system that are bigger than our own moon, and that we can see surface features like craters or mountains on many of them by going close to them with spacecraft. Further, I like them to appreciate that ongoing scientific research is discovering more of these moons out in space and showing us drastically new things about the properties of the ones we know. These are also basic concepts and not just vocabulary. And these are concepts that bring students the idea that science is interesting and exciting to study, for new things are being found.

I would be interested in setting up a discussion on the fundamental matter as to whether these are indeed important matters to teach students in the elementary grades, worth the time we commonly take to overcome difficulties caused by the phase of their intellectual development.

Zeilik.
I have a research result that should make you happy. In my introductory astronomy course for non-science majors, I use Project STAR-like questions on pre- and post-tests. The gains are enormous: about 3 standard deviations of gain with an effect size of about 2!

Sadler.
It is wonderful to hear of successes like yours. No doubt, it is the result of your emphasis on both cooperative learning and explicit learning objectives. I think it is very valuable to use others' tests in assessing one's own students. Students can quickly learn to answer the type of questions that the teacher normally asks in class. By using others' test items, especially those that measure changes in misconceptions or apply astronomical concepts to terrestrial situations, we better serve our students. I am happy to send a report on such tests to anyone who contacts me.